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Orthogonal LTE two-tier Cellular Networks

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***Abstract*—In previous works, Vandermonde-subspace frequency division multiplexing (VFDM) has been shown to promote overlay networks by enabling a secondary transmitter to cancel its interference to a primary receiver, while simultaneously transmitting useful information to its own receiver at non-negligible rates. Interference cancelation is achieved by exploiting the null-space of the channel from the secondary transmitter to the primary receiver. In the wake of a global deployment of the third generation partnership project's (3GPP) long term evolution (LTE), one of the open questions of VFDM concerns its applicability in a primary LTE-orthogonal frequency division multiple access (OFDMA) multi-user setting. In this work, we address this question by extending VFDM to the multi-user scenario where the primary system employs OFDMA, such as LTE. We show that by using at the secondary system a similar precoder structure to the ones previously introduced, we are able to cancel the interference towards multiple primary receivers while still achieving acceptable rates for the secondary system.**

I. Introduction

Since the dawn of telecommunications the electromagnetic radio spectrum has been the most important resource available to wireless communications system designers. In recent years managing radio spectrum has become a tough problem as a miriad of wireless standards have occupied all available bands. Furthermore, the Federal Communications Commissions (FFC) have shown that the already allocated radio spectrum is underutilized [1]. It has further concluded that the static radio spectrum allocation model adopted so far lacks efficiency and is not suitable to cope with the continuously increasing demands for higher-rate data services. One solution to this problem is to move to flexible spectrum management models, achieving higher spectral efficiencies by allowing wireless networks to operate in an overlay manner, supporting intelligent spectrum reuse [2].

Until a fully manageable dynamic spectrum allocation model is proposed, one widely accepted solution is to use cognitive radios [3]. Opportunistic cognitive radios can sense the environment and reason on a strategy to exploit free resources left over by the legacy system [4], [5]. In this framework the legacy system, who owns the right to the bandwidth, is called a *primary system* while the opportunistic system is called the *secondary system*. Spectrum access etiquette enforces that no secondary system can interfere with a primary system's transmission.

Cognitive radio can implement spectrum sharing through a number of techniques. The most prominently studied technique is called spectrum sensing, by which the secondary system can detect transmit opportunities, usually called spectrum holes. Nevertheless performing a correct detection of the spectrum holes can be difficult due to the presence of fading [6] or to the need to process multi-gigahertz wide bandwidth and reliably detect presence of primary users [7], imposing servere constraints to the sensitivity and linearity of the RF circuitry. A suggested approach to overcome the first issue is a technique called collaborative spectrum sensing but the parameters needed to sufficiently improve the model are yet to be found [8]. There are other techniques that can be used to implement a cognitive radio system, if the secondary network knows the maximum allowed interference level at the primary receiver or has the prior knowledge of the message to be transmitted, techniques such as interference temperature [9] or dirty paper coding [10] can be used, but unfortunately they both rely on very unrealistic assumptions. Another possible approach is the use of the left over degrees of freedom not exploited by the primary network.

In [11]–[13], we have proposed a technique to exploit the available frequential left-over dimensions to achieve spectrum sharing. Vandermonde-subspace frequency division multiplexing (VFDM), uses a linear Vandermonde-based precoder to project the signal to the secondary receiver on the null space of the interfering channel from the secondary transmitter to the primary receiver. VFDM benefits from the frequency selectivity of the channel to create a sort of frequency beamformer (similar to the classical spatial beamformer), and it can be applied to block transmission systems that exploit the redundancy provided by the introduction of a guard time, cyclic prefix or zero-padding.

In this contribution, we extend the work in [11]–[13] by considering a multi-user primary system based on orthogonal frequency division multiple access (OFDMA), such as the long term evolution (LTE) [14]. Nevertheless, the results presented in this paper are extendable to any OFDMA multi-user system. We devise a new precoder, similar to the VFDM one, able to cope with multiple users in the primary network and we show that zero-interference can still be achieved, along with a non-negligible rate for the secondary receiver.

This work is organized as follows. In Sec. II we introduce the model assumed throughout this paper. We then briefly review the concepts behind VFDM and extend them to derive a new precoder in Sec. III. In Sec. IV we analyze the performance. In Sec. V we present and discuss some numerical results and finally, conclusions and further research directions are discussed in Sec. VI.

II. System Model

Consider the LTE-like OFDMA downlink scenario depicted in Fig. 1, where a secondary system is added to communicate over the same bandwidth. The secondary system may not generate interference at the primary OFDMA one, while the latter is unaware of the existence of the secondary system and, having the rights to the spectrum, does not need to avoid interference to it.

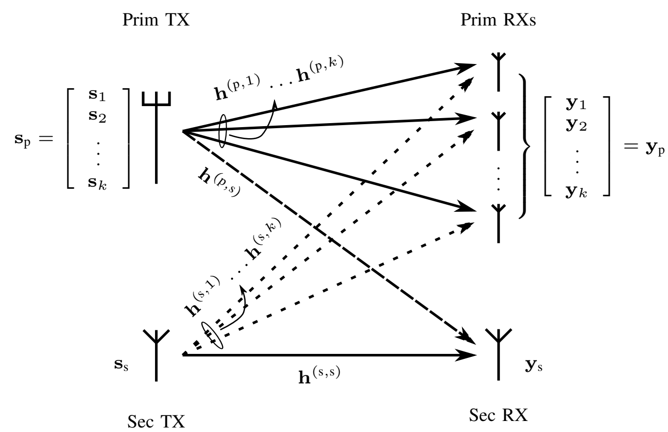

Fig. 1. LTE-like OFDMA downlink cognitive interference channel model

Let $\mathbf{h}^{(\mathrm{p},i)}$ denote the channel vector between the primary transmitter and receiver i, $\mathbf{h}^{(\mathrm{s},i)}$ the channel between the secondary transmitter and primary receiver i, $\mathbf{h}^{(\mathrm{s},\mathrm{s})}$ the channel between the secondary transmitter and receiver and $\mathbf{h}^{(\mathrm{p},\mathrm{s})}$ the channel between the primary transmitter and secondary receiver. All channel vectors are independent and identically distributed (i.i.d.) between themselves and are composed of $L+1$ i.i.d. Gaussian, complex and circularly symmetric taps $\mathcal{CN}(0, \mathbf{I}_{L+1}/(L+1))$. Also indicated in Fig. 1, $\mathbf{s}_\mathrm{p}$ is a zero mean, unit norm aggregate primary transmitted symbol vector composed of all the individual symbol vectors $\mathbf{s}_i$, whereas $\mathbf{y}_\mathrm{p}$ is the aggregate primary received symbol vector, defined similarly. $\mathbf{s}_\mathrm{s}$ is a zero mean, unit norm secondary transmitted symbol vector while $\mathbf{y}_\mathrm{s}$ is the received data for the secondary transmission.

The primary transmitter employs a k-user OFDMA system of block size $N+L$ with an overall cyclic prefix of size L. For simplicity, an equal resource sharing is adopted, i.e. N/k subcarriers per primary receiver. The overall signal at primary receivers is

$$\mathbf{y}_\mathrm{p} = \mathbf{F}\left(\mathcal{T}'_\mathrm{p}\mathbf{A}\mathbf{F}^{-1}\mathbf{s}_\mathrm{p} + \mathcal{T}'_\mathrm{s}\mathbf{V}\mathbf{s}_\mathrm{s} + \mathbf{n}_\mathrm{p}\right). \tag{1}$$

Concerning (1), $\mathbf{F} \in \mathcal{C}^{N\times N}$ is a FFT matrix, $\mathbf{n}_\mathrm{p}$ is a N-sized AWGN noise vector $\mathbf{n}_\mathrm{p} \sim \mathcal{CN}(0, \sigma\mathbf{I}_N)$, $\mathbf{A}$ is a $(N+L)\times N$ cyclic prefix precoding matrix, $\mathbf{V} \in \mathcal{C}^{(N+L)\times L}$ is a linear precoder and $\mathbf{s}_2$ is a unitary norm symbol vector.

$\mathcal{T}(\mathbf{h}^{(\cdot,\cdot)}) \in \mathcal{C}^{N\times(N+L)}$ is a Toeplitz matrix constructed from the $\mathbf{h}^{(\cdot,\cdot)}$ channel coefficients given by

$$\mathcal{T}(\mathbf{h}^{(\cdot,\cdot)}) = \begin{bmatrix} h_L^{(\cdot,\cdot)} & \cdots & h_0^{(\cdot,\cdot)} & 0 & \cdots & 0 \\ 0 & \ddots & & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & & \ddots & 0 \\ 0 & \cdots & 0 & h_L^{(\cdot,\cdot)} & \cdots & h_0^{(\cdot,\cdot)} \end{bmatrix},$$

$\mathcal{T}'_\mathrm{p} \in \mathcal{C}^{(N+L)\times N+L}$ is Toeplitz-like matrix of structure

$$\mathcal{T}'_\mathrm{p} = \begin{bmatrix} h_L^{(\mathrm{p},1)} & \cdots & h_0^{(\mathrm{p},1)} & 0 & \cdots & 0 \\ 0 & h_L^{(\mathrm{p},1)} & \cdots & h_0^{(\mathrm{p},1)} & \ddots & \\ \vdots & & \ddots & \ddots & & \vdots \\ & \ddots & h_L^{(\mathrm{p},k)} & \cdots & h_0^{(\mathrm{p},k)} & 0 \\ 0 & \cdots & 0 & h_L^{(\mathrm{p},k)} & \cdots & h_0^{(\mathrm{p},k)} \end{bmatrix}$$

obtained by selecting the lines from each of the k Toeplitz matrices $\mathcal{T}(\mathbf{h}^{(\mathrm{p},i)})$ that correspond to the sub-carrier user allocation. $\mathcal{T}'_\mathrm{s}$ is a similarly structured Toeplitz-like matrix, and it is the equivalent channel from the secondary transmitter to the primary receivers, due to the orthogonality inherent to the user resource allocation in the frequency domain, proper of OFDMA.

Concerning the secondary system, a point-to-point $(N+L)$-sized block transmission scheme is adopted with the first L symbols discarded to avoid block interference. The received signal at the secondary receiver is

$$\mathbf{y}_\mathrm{s} = \mathbf{F}\left(\mathcal{T}(\mathbf{h}^{(\mathrm{s},\mathrm{s})})\mathbf{V}\mathbf{s}_\mathrm{s} + \mathcal{T}(\mathbf{h}^{(\mathrm{p},\mathrm{s})})\mathbf{A}\mathbf{F}^{-1}\mathbf{s}_\mathrm{p} + \mathbf{n}_\mathrm{s}\right). \tag{2}$$

Regarding (2), as defined for the primary system, $\mathbf{n}_\mathrm{s}$ is a N-sized AWGN noise vector $\mathbf{n}_\mathrm{s} \sim \mathcal{CN}(0, \sigma\mathbf{I}_N)$.

Our objective is to find a linear precoder for the secondary transmitter that can be used in order to cancel the interference at the primary receivers. Therefore, we must find a $\mathbf{V}$ such that for any $\mathbf{s}_\mathrm{s}$, we effectively satisfy the orthogonal condition

$$\mathcal{T}'_\mathrm{s}\mathbf{V} = \mathbf{0}. \tag{3}$$

III. Precoder Design

It is clear from (3) that such a precoder needs to be on the null-space of the interfering channel. We have shown in [11], [13] that we can easily design this precoder using a Vandermonde matrix [15] whose structure is

$$\mathbf{V} = \begin{bmatrix} 1 & \cdots & 1 \\ a_1 & \cdots & a_L \\ a_1^2 & \cdots & a_L^2 \\ \vdots & \ddots & \vdots \\ a_1^{N+L-1} & \cdots & a_L^{N+L-1} \end{bmatrix},$$

where $\{a_1, \ldots, a_L\}$ are the roots of the polynomial in z

$$S(z) = \sum_{i=0}^{L} h_i z^{L-i},$$

with $L+1$ coefficients of the interfering channel h_i. Unfortunately this result is not applicable to the OFDMA case presented in this paper, since now multiple interfering channels are present, instead of only one. However, other techniques allow for a such a precoder $\mathbf{V}$ to be devised, as we will show in the following. These techniques were further explored in previous works for similar purposes [13], [16].

Differently from what we do in [11], we derive the intended precoder using the singular value decomposition (SVD) of the channel matrix $\mathcal{T}(\mathbf{h}^{(\mathrm{s,p})})$. If we let $\mathcal{T}(\mathbf{h}^{(\mathrm{s,p})}) = \mathbf{U}\boldsymbol{\Lambda}^{1/2}\mathbf{D}^{\mathrm{H}}$, where $\mathbf{U} \in \mathcal{C}^{N\times N}$ and $\mathbf{D}^{\mathrm{H}} \in \mathcal{C}^{(N+L)\times(N+L)}$ are unitary matrices, in particular $\mathbf{D}$ has the form $[\ \mathbf{d}_1 \mid \mathbf{d}_2 \mid \cdots \mid \mathbf{d}_{N+L}\ ]$ (i.e., $\mathbf{d}_j$ is the jth column of $\mathbf{D}$). Then, by defining

$$\mathbf{V} \triangleq [\ \mathbf{d}_{N+1} \mid \cdots \mid \mathbf{d}_{(N+L)-1} \mid \mathbf{d}_{N+L}\ ],$$

we are picking the L directions associated to the L vectors which span $\ker \mathcal{T}(\mathbf{h}^{(\mathrm{s,p})})$. This ensures the compliance to the null condition in Eq. (3). Note that the construction of $\mathbf{V}$ requires full channel state information at the secondary transmitter (CSIT) related to the interfering channels towards the primary receivers. This could be accomplished by pilot estimation, when these primary receivers send pilots back to the OFDMA transmitter on the uplink using time division duplex (TDD).

By plugging the precoder into (1), we get

$$\mathbf{y}_{\mathrm{p}} = \mathbf{H}_{\mathrm{p}}\mathbf{s}_{\mathrm{p}} + \nu_{\mathrm{p}}, \tag{4}$$

where $\mathbf{H}_{\mathrm{p}} = \mathbf{F}\mathcal{T}'_{\mathrm{p}}\mathbf{A}\mathbf{F}^{-1} \in \mathcal{C}^{N\times N}$ is the overall primary OFDMA channel and ν_{p} is the Fourier transform of the noise $\mathbf{n}_{\mathrm{p}}$, has the same statistics as $\mathbf{n}_{\mathrm{p}}$.

In this work we are essentially interested in the secondary link (as the performance of the primary system is well known) and thus we concentrate on $\mathbf{y}_{\mathrm{s}}$. We can rewrite $\mathbf{y}_{\mathrm{s}}$ as

$$\mathbf{y}_{\mathrm{s}} = \mathbf{H}_{\mathrm{s}}\mathbf{s}_{\mathrm{s}} + \mathbf{H}_{\mathrm{p,s}}\mathbf{s}_{\mathrm{p}} + \nu_{\mathrm{s}}, \tag{5}$$

where $\mathbf{H}_{\mathrm{s}} = \mathcal{T}(\mathbf{h}^{(\mathrm{s,s})})\mathbf{V} \in \mathcal{C}^{N\times L}$ is the overall channel matrix for the secondary system, $\mathbf{H}_{\mathrm{p,s}} = \mathbf{F}\mathcal{T}(\mathbf{h}^{(\mathrm{p,s})})\mathbf{A}\mathbf{F}^{-1} \in \mathcal{C}^{N\times N}$ is the diagonal overall channel matrix for the primary system (interference w.r.t. the secondary receiver) and ν_{s}, the Fourier transform of the noise $\mathbf{n}_{\mathrm{s}}$, has the same statistics as $\mathbf{n}_{\mathrm{s}}$.

In the next section we calculate the performance of the secondary system in this scenario.

IV. Performance Analysis

In order to find the maximum achievable rate for the secondary system we have focused on its input covariance optimization. The primary system's maximum achievable rate is known since our precoder allows the primary system to be considered as N parallel channels whose capacity is known to be maximized by a classical water-filling algorithm. The secondary receiver, however, has no knowledge of the primary system's message, hence, it performs single-user decoding, i.e., considering the interference as noise. Let $\boldsymbol{\eta}$ indicate the interference plus noise component of the message at the secondary receiver. Then (5) becomes

$$\mathbf{y}_{\mathrm{s}} = \mathbf{H}_{\mathrm{s}}\mathbf{s}_{\mathrm{s}} + \boldsymbol{\eta}.$$

Considering that a Gaussian constellation is adopted for all transmit symbols, and the effective channel from the primary transmitter to the secondary receiver is diagonal, we can effectively assume that the overall noise is Gaussian. We can safely approximate $\boldsymbol{\eta}$ to a zero-mean Gaussian random vector with covariance given by

$$\mathbf{S}_{\eta} = \mathbf{H}_{\mathrm{p,s}}\mathbf{S}_{\mathrm{p}}\mathbf{H}_{\mathrm{p,s}}^{\mathrm{H}} + \mathbf{I}_N.$$

To evaluate the impact of our precoder on the performance of the secondary system, we adopt a Gaussian input signal $\mathbf{s}_{\mathrm{s}}$ of covariance $\mathbf{S}_{\mathrm{s}}$ and assume perfect knowledge of $\mathbf{S}_{\eta}$ at the secondary transmitter.

Let P_{s} be the transmit power per symbol. Then, the maximum achievable rate of the secondary system is the solution of the following maximization problem

$$\begin{aligned}\max_{\mathbf{S}_{\mathrm{s}}} \quad & \frac{1}{N+L}\log_2\left|\mathbf{I}_N + \mathbf{S}_{\eta}^{-1/2}\mathbf{H}_{\mathrm{s}}\mathbf{V}\mathbf{S}_{\mathrm{s}}\mathbf{V}^{\mathrm{H}}\mathbf{H}_{\mathrm{s}}^{\mathrm{H}}\mathbf{S}_{\eta}^{-\mathrm{H}/2}\right| \\ \text{s.t.} \quad & \operatorname{tr}(\mathbf{V}^{\mathrm{H}}\mathbf{V}\mathbf{S}_{\mathrm{s}}) \le (N+L)P_{\mathrm{s}}\end{aligned}$$

.

The given problem is convex, but the presence of the term $\mathbf{V}^{\mathrm{H}}\mathbf{V}$ in the constraint does not allow us to apply directly a water-filling algorithm [17].

In order to convert the problem into a more tractable form, we let $\mathbf{G} = \mathbf{S}_{\eta}^{-1/2}\mathbf{H}_{\mathrm{s}}\mathbf{V}$ and $\mathbf{G} = \mathbf{U}_{\mathrm{g}}\boldsymbol{\Lambda}_{\mathrm{g}}^{1/2}\widetilde{\mathbf{V}}_{\mathrm{g}}^{\mathrm{H}}$ be its SVD, where $\mathbf{U}_{\mathrm{g}} \in \mathcal{C}^{N\times N}$, $\widetilde{\mathbf{V}}_{\mathrm{g}} \in \mathcal{C}^{L\times L}$ are unitary matrices and $\boldsymbol{\Lambda}_{\mathrm{g}}$ is diagonal with $r \le L$ eigenvalues $\lambda_{\mathrm{g},i} > 0$. Then, we let $\mathbf{S}_{\mathrm{s}} = \widetilde{\mathbf{V}}_{\mathrm{g}}\mathbf{P}\widetilde{\mathbf{V}}_{\mathrm{g}}^{\mathrm{H}}$, where $\mathbf{P} \in \mathcal{R}^{L\times L}$ is diag $[p_1, \ldots, p_L]$.

We can plug the new definition of $\mathbf{S}_{\mathrm{s}}$ into the optimization problem and constraint to get

$$\begin{aligned}\max_{\mathbf{P}} \quad & \frac{1}{N+L}\log_2\left|\mathbf{I}_N + \mathbf{U}_{\mathrm{g}}\boldsymbol{\Lambda}_{\mathrm{g}}^{1/2}\mathbf{P}\boldsymbol{\Lambda}_{\mathrm{g}}^{\mathrm{H}/2}\mathbf{U}_{\mathrm{g}}^{\mathrm{H}}\right| \\ \text{s.t.} \quad & \operatorname{tr}(\mathbf{Q}\mathbf{P}) \le (N+L)P_{\mathrm{s}},\end{aligned}$$

where we have introduced the simplification $\mathbf{Q} = \widetilde{\mathbf{V}}_{\mathrm{g}}^{\mathrm{H}}\mathbf{V}^{\mathrm{H}}\mathbf{V}\widetilde{\mathbf{V}}_{\mathrm{g}}$. Finally, the initial optimization problem can be cast into a new one given by

$$\begin{aligned}\max_{p_i} \quad & \log_2(1+\lambda_{\mathrm{g},i}p_i) \\ \text{s.t.} \quad & \sum_{i=1}^{L} p_i q_{ii} \le (N+L)P_{\mathrm{s}}.\end{aligned} \tag{6}$$

Now we can apply the classical water-filling algorithm [17]. The solution to (6) is given by a covariance matrix $\mathbf{S}_{\mathrm{s}} = \widetilde{\mathbf{V}}_{\mathrm{g}}\mathbf{P}\widetilde{\mathbf{V}}_{\mathrm{g}}^{\mathrm{H}}$, where the $i-$th component of the matrix $\mathbf{P}$ is the weighted water-filling solution

$$p_i = \left[\frac{\mu}{q_i} - \frac{1}{\lambda_{\mathrm{g},i}}\right]^{+}, \tag{7}$$

and μ is the "water level", determined to fulfill the total power constraint $(N+L)P_{\mathrm{s}}$. Once the optimal solution using our derived weighted water-filling algorithm has been found, the maximum achievable rate for the secondary system is given by

$$R_2 = \frac{1}{N+L}\sum_{i=1}^{L}\log_2(1+\lambda_{\mathrm{g},i}p_i) \tag{8}$$

.

V. Numerical Results

In this section we provide some numerical results to illustrate the performance of our precoder design. We consider an LTE (OFDMA) primary system with a varying number of users $k = \{1, 2, 4, 8, 16, 32, 64\}$ based on the transmission mode with a bandwidth of 1.42 MHz, characterized by $N = 128$ active subcarriers and a cyclic prefix of length $L = 32$ (extended mode), better described in [14]. For the simulations, we generated channels and noise according to the definitions made in Sec. II, controlling the signal to noise ratio (SNR) by changing the value of σ. Monte Carlo based simulations are executed until 10000 iterations are reached yielding a statistically sufficient amount of samples. Moreover, we recall that perfect knowledge (CSIT) of all channels involved at the secondary transmitter is assumed.

A. Primary versus Secondary System

In Fig. 2 the sum rate of the primary system is presented for a total of $k = 8$ users along with the rate of the secondary receiver for different values of the SNR. Note that the choice of representing only the rate of the primary system for the $k = 8$ case makes sense since the sum rate is independent from k. We see that the difference in rate between the primary system and the secondary receiver is of about 1/4 as the SNR increases. This behavior can be easily explained and justified if we consider the parameter of the simulated LTE mode. In fact, the ratio between the transmitted symbols of the primary system $N = 128$, and the ones of the secondary system $L = 32$, is exactly $\frac{L}{N}$ =1/4. Moreover this result is compliant with our previous findings in [11], [13].

B. Affect of the Number of Primary Receivers

In Fig. 3 we show the secondary receiver's rate with respect to the number of primary receivers for different values of the SNR $= \{0, 10, 20, 30\}$. As expected, the rate remains rather constant with the increase of the number of users, with only a slight drop in rate for lower numbers of primary receivers (i.e. $k < 8$). This behavior is due to the greater channel diversity seen in the $k \geq 8$ case, and it implies that for a big number of primary receivers the designed precoder performs slightly better in terms of rate. Furthermore, the slope of the drop is very low and the difference is negligible if compared to the rate achievable by the secondary receiver. As expected, the drop is more pronounced in the high SNR regime, but the slope is still very low.

C. Single Primary Receiver versus Secondary Receiver

Now we shift the focus to the comparison of the secondary receiver's performance with respect to a single primary receiver in a multi-receiver OFDMA case as seen in Fig. 4. Therein, we see that, the greater the amount of users in the primary system, the better the performance of the secondary one w.r.t. a single primary. This behavior is expected, since while in the primary system the resources are equally shared among receivers, this does not happen in the secondary system where there is only one receiver. Moreover, as we have seen in the previous figures, even if the secondary receiver's rate does not vary a lot with respect to the number of users, it is slightly higher when $k > 8$. Note that we are operating in the extendend mode of the least demanding configuration of LTE in terms of bandwidth, even though the secondary receiver

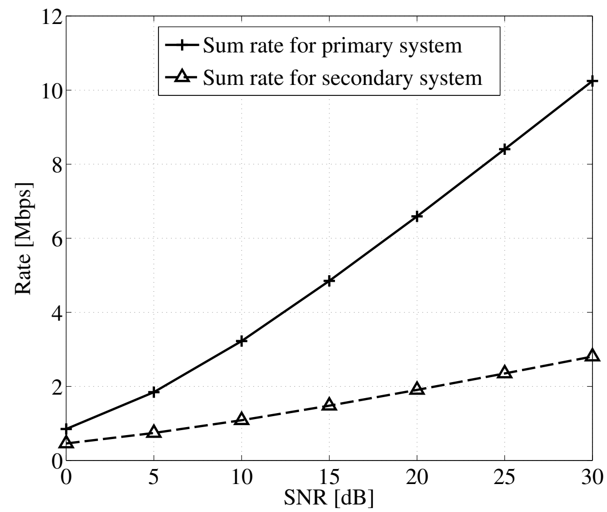

Fig. 2. Sum rate of the primary system in a 8-receiver OFDMA configuration compared to the secondary receiver's rate ($N = 128, L = 32$ and bandwidth of 1.42 Mhz)

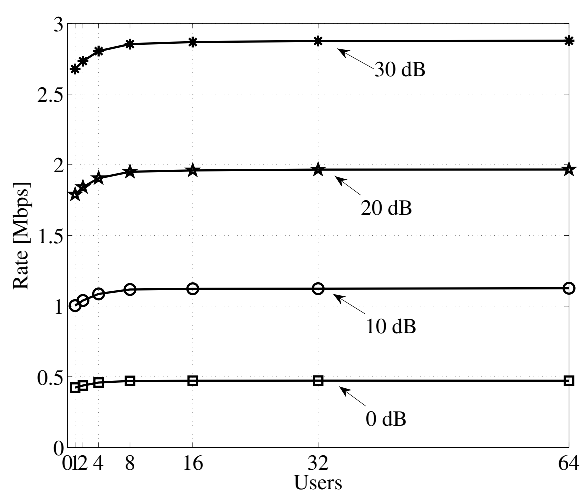

Fig. 3. Rate of the secondary system for increasing number of primary receivers and several SNR values ($N = 128, L = 32$ and bandwidth of 1.42 Mhz)

can achieve a rate of almost 3 Mbps in the high SNR regime, which is a non-neglible rate. Furthermore, starting from the rather low number of $k = 4$, which expectedly corresponds to the proportion of carriers to the cyclic prefix symbols, the secondary system becomes competitive. This is a promising result, since $k \geq 4$ primary receivers is a reasonably realistic operating scenario.

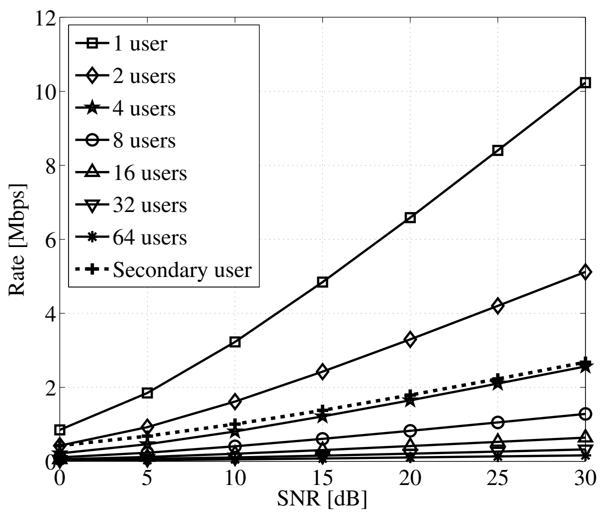

Fig. 4. Rate of the primary system for different number of receivers compared to the secondary receiver's rate ($N = 128, L = 32$ and bandwidth of 1.42 Mhz)

VI. Conclusions

As shown in this work, the presented technique offers a good performance provided that it exploits the left-over degrees of freedom by the primary system at no cost. We have extended the work presented in [11] showing that VFDM can be successfully used by a secondary user dealing with a primary LTE/OFDMA multi-user system. We have derived a solution using a weighted water-filling algorithm that allows a secondary non-licensed cognitive-like system performing VFDM to achieve a non-negligible rate, at the sole cost of perfect CSIT. Furthermore, we have shown that in a high-user realistic setting, the secondary system has a competitive advantage if compared to a single primary receiver's rate.

Our next challenge for the future is a further extension of this work to a multi-user secondary sytem based on VFDM. Moreover, we will study the performance of the secondary system with imperfect CSIT, together with the introduction of a realistic ITU-T channel model. All these results will allow us to start the implementation of a transmission testbed based on VFDM as a proof of concept.

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